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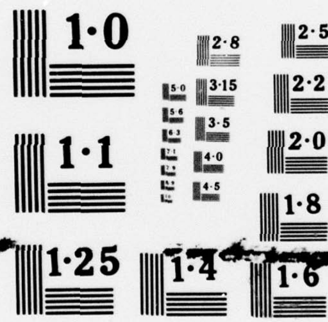
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## THE RESPONSE OF THE COASTAL WATERS OF NORTHWEST ITALY.

by

10 ALAN J. ELLIOTT

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# THE RESPONSE OF THE COASTAL WATERS OF NORTHWEST ITALY

by

Alan J. Elliott



15 November 1978

This memorandum has been prepared within the SACLANTCEN Underwater Research Division.



G.C. VETTORI
Division Chief

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# THE RESPONSE OF THE COASTAL WATERS OF NORTHWEST ITALY *

by

Alan J. Elliott

## ABSTRACT

*Two-month long low-pass records of the coastal currents and winds have been analysed for two locations off the northwestern coast of Italy. Most of the energy was found to be in the long period (>20 day) motions and there was low coherence between the currents and wind except for time scales around 5 days. This suggests that either the wind was exciting a rotational mode of the entire Western Mediterranean or else that the weather systems were more coherent spatially at the 5-day time scale. A depth-integrated hydrodynamic model is being used to resolve the time scales and the effects of bottom topography. The coastal currents may make a significant contribution to the day-to-day variability in sound speed, especially near frontal zones, due to the alongshore advection of water of differing acoustic properties. Consequently, accurate prediction of the sound speed at a fixed location may not be obtained until the coastal dynamics are clearly understood.*

## INTRODUCTION

During recent years there has been an increasing interest in problems related to shallow-water acoustics. As a result, two distinct problem areas have arisen, which need to be addressed by the research. The first of these involves the acoustic propagation itself, the second is more oceanographic in nature and concerns the variability of the acoustic properties of the water near a coast. In the deep ocean, for many acoustic purposes, the water can be considered as being well-mixed in the horizontal plane and only the vertical variations need to be considered. Thus the majority of sonar models do not incorporate range-dependent temperature fields and variable bottom topography but, instead, use a single, vertical temperature profile and a flat bottom to characterize a region of interest. For many purposes this is an acceptable approximation, but it is not generally valid in shallow water. In the coastal zone, as well as the complicating effect of a sloping bottom, there can be significant variations in the salinity, temperature, and sound-speed characteristics of the water over relatively short horizontal

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* *Paper presented at the Tenth International Liège Colloquium on Ocean Hydrodynamics, The University of Liège, 8-12 May, 1978.*

distances. Among the mechanisms that can cause the variations are the fresh water input by rivers, upwelling induced by the coastal winds, and the enhanced vertical mixing due to the strong tidal and storm-generated currents. As a result, the coastal zone is usually a region of high acoustic variability. The problem is complicated further since the coastal waters are not static but are constantly being moved by the coastal currents under the influence of the winds. Consequently, owing to the combined effect of the high spatial variability in the sound speed and the advective effects of the currents, measurements made at a selected location on one day may not be valid for the following day.

For the oceanographer there are two distinct problems to be resolved: first, can we obtain insight into the mechanisms that lead to the high variability in the coastal waters, e.g. the processes that generate fronts; second, given that high spatial variability exists in the coastal waters, what are the time scales associated with the coastal currents that would contribute to the temporal acoustic variability at a fixed location, and to what extent can we succeed in modelling the dynamics of the coastal response?

In order to answer some of these questions, and to provide an oceanographic input into what is essentially an acoustic problem area, a series of field measurements were made in the coastal waters of northwest Italy and this has been combined with a numerical study of the region. The purpose of this paper is to present some of the observational results and show that, in general, there was a lack of coherence between the coastal currents measured at different locations. The second part of the paper describes how a depth-integrated numerical model is being used to resolve the role that might be played by the variations in bottom topography: one of the factors that may have contributed to the low coherence in the measurements.

## 1 OBSERVATIONS

During April and May 1977 current measurements were made at two locations off the northwestern coast of Italy in water approximately 100 m deep and 15 km offshore. The two moorings, which were 100 km apart, were located near Elba on opposite sides of the shallow water that extends between the Italian mainland and the island of Corsica (Fig. 1). Three oceanographic cruises were made at approximately monthly intervals to survey the temperature/salinity properties of the coastal waters near the mooring positions, and meteorological and sea level data were obtained from established coastal recording stations. Each mooring supported two current meters: one at a depth of 20 m and the other at 80 m. The data series were filtered with a low-pass filter to remove the fluctuations with periods of less than two days; the data were then resampled at 6-hour intervals.

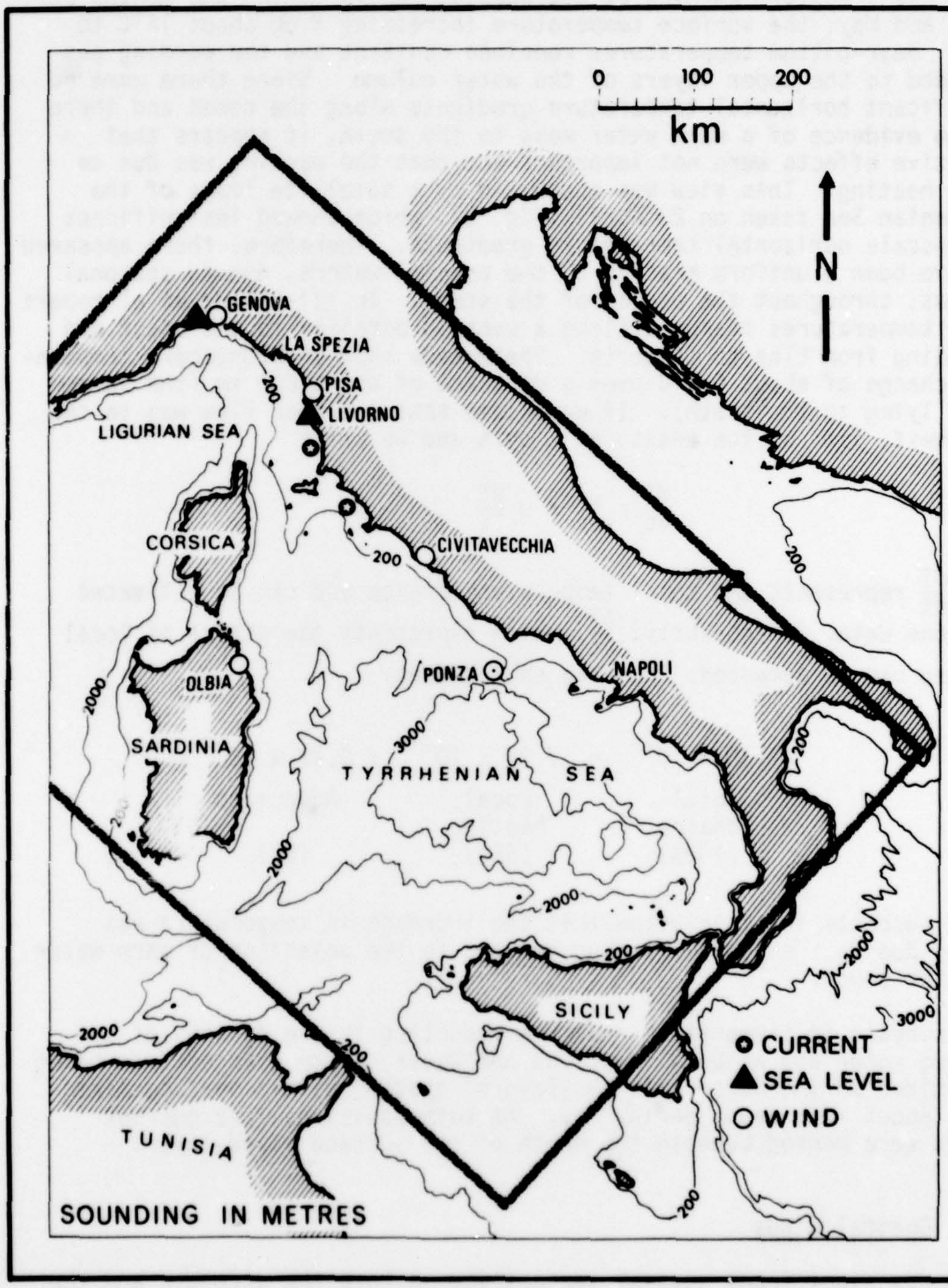


***FIG. 1 THE LIGURIAN AND TYRRHENIAN SEAS SHOWING THE MOORING LOCATIONS. The dashed line represents the boundary of the numerical model.***

## 1.1 Hydrography

There was a uniform warming of the coastal waters during the months of April and May, the surface temperature increasing from about 14°C to 18°C. Near-bottom temperatures remained constant and the warming was confined to the upper layers of the water column. Since there were no significant horizontal temperature gradients along the coast and there was no evidence of a warm water mass to the south, it appears that advective effects were not important and that the warming was due to solar heating. This view was supported by a satellite image of the Tyrrhenian Sea taken on 23 April (Fig. 2), which showed insignificant large-scale horizontal temperature gradients. Therefore, there appeared to have been a uniform heating of the coastal waters, due to seasonal changes, throughout the period of the study. In *[1]* Miller et al report water temperatures measured along a section parallel to the coast and extending from Elba to Calabria. Their data show an alongshore temperature change of about 0.5°C over a distance of about 600 km (the warmer water lying to the south). If we assume that the mean flow was to the northwest, i.e. up the coast, at 5 cm/s and we write

$$\frac{dT}{dt} = \frac{\partial T}{\partial t} + u\,\frac{\partial T}{\partial x} \;,$$

then $\frac{dT}{dt}$ represents the total temperature change and can be estimated from the data. Consequently, $\frac{\partial T}{\partial t}$, which represents the effect of local heating can be computed. The data showed that:

$$\underset{\substack{\text{Total}\\ \text{change}\\ (100\%)}}{7.70 \times 10^{-7}} = \underset{\substack{\text{Local}\\ \text{heating}\\ (95\%)}}{7.28 \times 10^{-7}} + \underset{\substack{\text{Advection}\\ \\ (5\%)}}{0.42 \times 10^{-7}} \;,$$

which supports the conclusion that the increase in temperature was mainly due to a seasonal warming and not to the advection of warm water from the south.

The increase in temperature caused a reduction in the density of the surface water and at both locations the water column changed from being well-mixed during March to a two-layered system, with a surface mixed-layer about 10 m deep, during May. At both positions, the current meters were moored beneath the depth of the surface mixed-layer.

## 1.2 Coastal Winds

There was significant spatial variability in both the strength and the direction of the low-pass coastal winds. Whereas the mean stress at the three southern stations (Civitavecchia, Olbia, and Ponza) was directed eastwards with a strength of about 0.5 dyne/cm$^2$, the mean stress at Genova and Pisa was about an order of magnitude weaker; at Pisa the mean stress vector was directed towards the northeast while at Genova it was

*FIG. 2 INFRARED SATELLITE IMAGE OF THE TYRRHENIAN SEA, 23 APRIL, 1977. The warm water masses show up as darker patches, parts of Sicily and Calabria are cloud covered (courtesy of the University of Dundee).*

towards the northwest. The anticlockwise rotation of the mean wind may have been caused by cyclogenesis *[2]*, or it may have been due to orographic effects. To resolve the structure of the wind, empirical orthogonal function analysis *[3]* was applied to the five components of east-west stress. Of the five modes isolated (since there were five input series), the first mode was highly correlated with the components of stress at Pisa, Civitavecchia, Olbia, and Ponza, but explained only 1% of the variance in the Genova record. In contrast, the second mode accounted for 95% of the Genova variance but was uncorrelated with the other locations. A similar result was obtained when the analysis was repeated for the north-south components of stress.

As a result of this partition of the wind records it was decided that the Genova wind was not representative and that the record had been unduly influenced by orographic effects; it was therefore excluded from further analysis. The remaining four vector series were then averaged to produce a time series of the large-scale wind. The geostrophic wind stress, calculated from atmospheric pressure, was not coherent with the observed wind and was a poor predictor of the current response.

## 1.3 Coastal Currents

Figure 3 shows the low-pass alongshore components of the currents and mean wind, positive currents and wind stress being directed up the coast towards the northwest. The current records showed marked fluctuations at a time scale comparable to the record length, while the wind appeared to contain more energy at the shorter time scales. The flow was northwards when the wind was near zero and reversed its direction only during strong southward winds. Linear regression showed that under conditions of zero wind the flow would be towards the northwest at both mooring locations, and that this density-driven flow, which appeared to be independent of depth, had a strength of about 5 cm/s.

Spectra for current, adjusted sea level, and atmospheric pressure at Livorno, and the alongshore wind are shown in Fig. 4; they indicate that the energy was contained in the longer-period motions. Sea level and wind spectra peaked at around 20 days, while the current and atmospheric pressure had maxima at periods comparable to the record length. The spectra decreased steadily between 20 days and 3 days; in particular, there was no pronounced spectral peak at the 5-day time scale. However, when the coherence was computed between pairs of variables then the coherence was usually greater at 5 days than at other periods. As an example, Fig. 5 shows the coherence between the alongshore wind and each of the four current records. At both the north and south mooring the bottom currents were highly coherent with the wind at the 5-day time scale. Comparable results were found when sea level and atmospheric pressure were analysed: the coherent response appeared to be confined to a band around the 5-day period. Since the forcing variables (e.g. wind and pressure) did not contain an excess of energy at this time scale it suggests that the coastal waters were responding in an organized manner to the 5-day forcing.

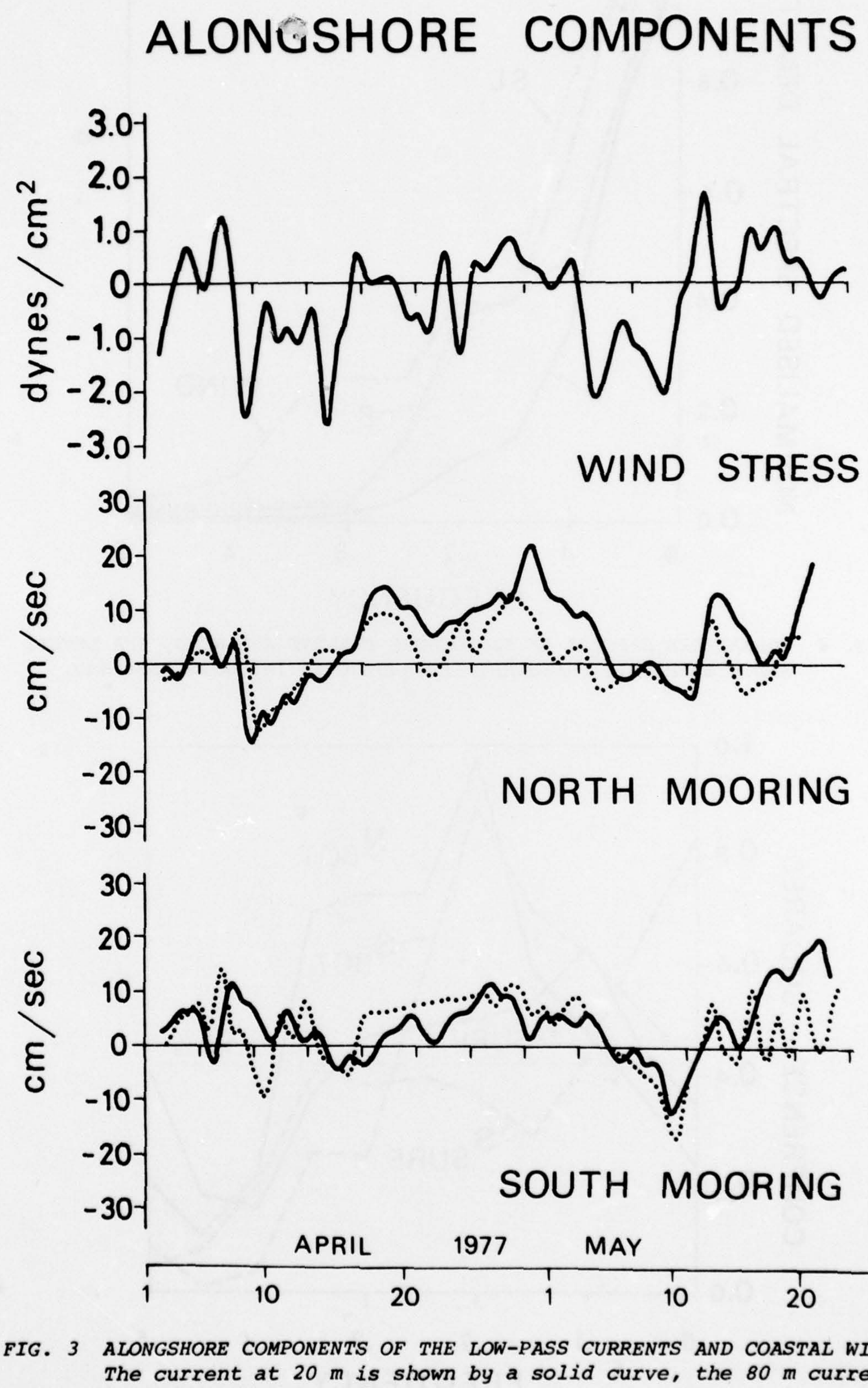


*FIG. 3 ALONGSHORE COMPONENTS OF THE LOW-PASS CURRENTS AND COASTAL WIND. The current at 20 m is shown by a solid curve, the 80 m current by a dotted curve.*

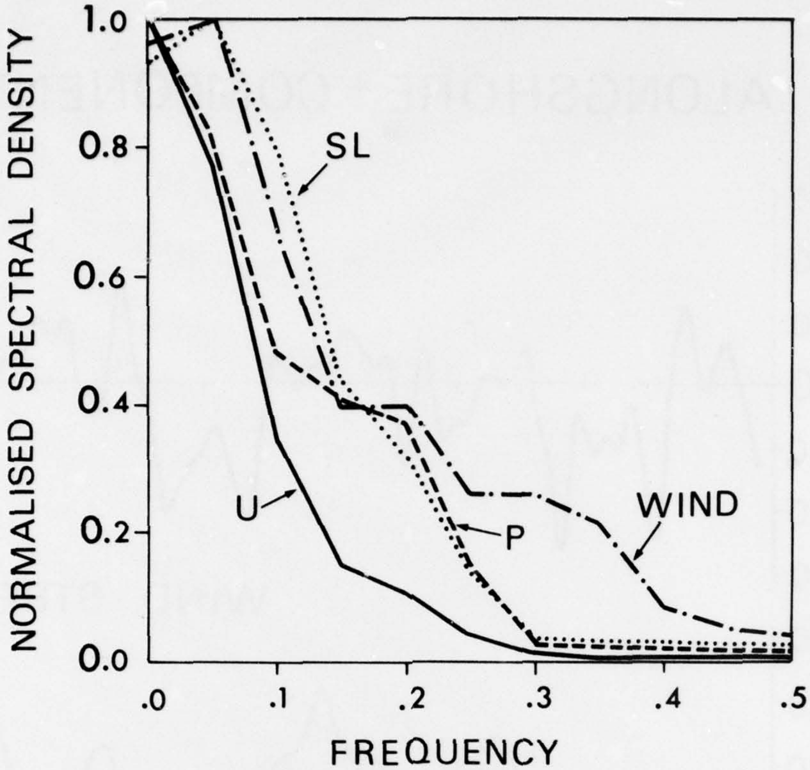


*FIG. 4 NORMALIZED SPECTRA OF ALONGSHORE CURRENT AND WIND, SEA LEVEL, AND ATMOSPHERIC PRESSURE. Frequency is in cycles per day.*

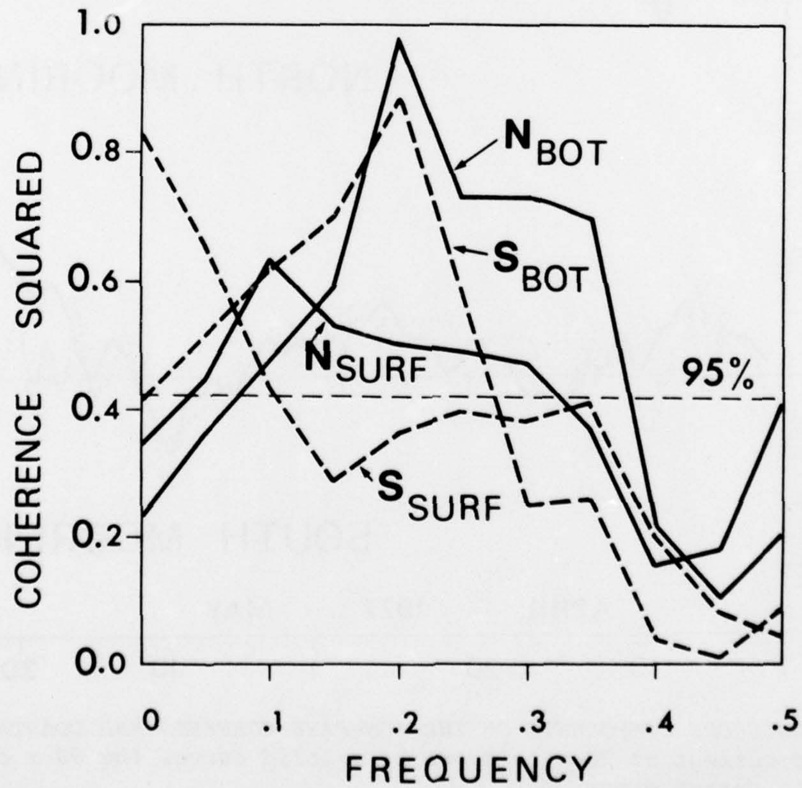


*FIG. 5 COHERENCE SQUARED BETWEEN THE ALONGSHORE CURRENTS AND ALONGSHORE WIND. N signifies the north mooring, S signifies the south mooring.*

## 2 A MODEL OF THE LIGURIAN AND TYRRHENIAN SEAS

Since the local bottom topography, the geometry of the deep basins, and rotational effects were suspected of being factors that could influence the currents, the problem is being approached numerically through the use of a hydrodynamic model. A depth-integrated model, suitable for general application to both deep and shallow water areas, was developed; the model includes density terms as well as a salinity balance and a temperature (or pollutant) balance equation. The full system of equations used in the study was:

$$\frac{\partial \eta}{\partial t} = (d+\eta)\,\frac{\sigma}{\rho} - \frac{\partial}{\partial x_1}\left[(d+\eta)u_1\right] - \frac{\partial}{\partial x_2}\left[(d+\eta)u_2\right] ,$$

$$\frac{\partial}{\partial t}\left[(d+\eta)u_1\right] = \frac{\partial}{\partial x_1}\left[(d+\eta)\,N\frac{\partial u_1}{\partial x_1}\right] + \frac{\partial}{\partial x_2}\left[(d+\eta)\,N\frac{\partial u_1}{\partial x_2}\right]$$
$$+ f(d+\eta)u_2 - g(d+\eta)\,\frac{\partial \eta}{\partial x_1} - \frac{g}{\rho}\,\frac{(d+\eta)^2}{2}\,\frac{\partial \rho}{\partial x_1} + FS_1 - FB_1 ,$$

$$\frac{\partial}{\partial t}\left[(d+\eta)u_2\right] = \frac{\partial}{\partial x_1}\left[(d+\eta)\,N\frac{\partial u_2}{\partial x_1}\right] + \frac{\partial}{\partial x_2}\left[(d+\eta)\,N\frac{\partial u_2}{\partial x_2}\right]$$
$$- f(d+\eta)u_1 - g(d+\eta)\,\frac{\partial \eta}{\partial x_2} - \frac{g}{\rho}\,\frac{(d+\eta)^2}{2}\,\frac{\partial \rho}{\partial x_2} + FS_2 - FB_2 ,$$

$$\frac{\partial}{\partial t}\left[(d+\eta)s\right] = \frac{\partial}{\partial x_1}\left[(d+\eta)\,K\frac{\partial s}{\partial x_1}\right] + \frac{\partial}{\partial x_2}\left[(d+\eta)\,K\frac{\partial s}{\partial x_2}\right]$$
$$- \frac{\partial}{\partial x_1}\left[(d+\eta)u_1 s\right] - \frac{\partial}{\partial x_2}\left[(d+\eta)u_2 s\right] ,$$

$$\frac{\partial}{\partial t}\left[(d+\eta)c\right] = \frac{\partial}{\partial x_1}\left[(d+\eta)\,K\frac{\partial c}{\partial x_1}\right] + \frac{\partial}{\partial x_2}\left[(d+\eta)\,K\frac{\partial c}{\partial x_2}\right]$$
$$- \frac{\partial}{\partial x_1}\left[(d+\eta)u_1 c\right] - \frac{\partial}{\partial x_2}\left[(d+\eta)u_2 c\right] + (d+\eta)\sigma_c ,$$

$$\rho = \rho_0(1 + \alpha s + \beta c) ,$$

where $u_1$ and $u_2$ are the components of the horizontal velocity, $\eta$ is the surface elevation above mean sea level, $d$ is the bottom depth with respect to mean sea level, $s$ is the salinity, and $c$ represents the concentration of a pollutant or, with some modification to the equation,

the temperature distribution. N and K represent the horizontal eddy stress and diffusivity. A term representing a fresh-water source was included in the continuity equation to allow for river run-off. The components of surface stress, $FS_1$ and $FS_2$, were calculated using a quadratic drag law for the wind stress, and $FB_1$ and $FB_2$ were the components of bottom stress — also quadratic in form. Consequently, the equations form a basically linear system with the exception of the quadratic friction term.

The equations were solved explicitly in a standard manner using a leap-frog scheme with centred space differences on a regular grid. The variables were spatially staggered on the grid so that surface elevation, density, and depth were specified at the centre of each rectangular element while the two velocity components were specified at the mid-points of adjacent sides of the grid elements *[4, 5, 6]*. Under many circumstances (including the present) density effects can be neglected, in which case only the first three equations need to be solved.

## 3 THE TIME SCALES OF THE LIGURIAN AND TYRRHENIAN BASINS

As a first step towards resolving the normal modes of the entire Western Mediterranean, the model was applied to the more restricted region comprising the Ligurian and Tyrrhenian Seas, as shown in Fig. 1. In addition, attention was directed towards the shorter time scales, i.e. those of about one day and less. The current observations discussed previously provided a problem of a qualitative nature to which the model could be applied. This was that, before the current records had been low-pass filtered, both progressive vector diagrams and spectral calculations had revealed a marked difference in the currents at the two mooring locations, especially during the first month of measurement. Whereas the currents at the northern mooring were generally of long period (>10 days) and flowed parallel to the coast-line (having twice as much energy in the alongshore direction as in the on/offshore), the currents at the southern mooring were mainly inertial with a period of around 17.5 hours. There was nearly an order of magnitude more inertial energy at the southern mooring than there was in the north, the tidal energy being insignificant at both locations.

Previous observations of inertial motions in the Mediterranean have shown that they are rarely coherent over horizontal scales exceeding 10 km. However, in the present case we are not investigating the coherence between inertial motions — we are, instead, seeking an explanation for the apparent lack of such motions at the north mooring.

To determine the spatial variability in the local response to forcing, the model was applied to the region shown in Fig. 6. For the boundary conditions there was assumed to be no flow through the Strait of Sicily, and the surface elevations along the left-hand open boundary were specified everywhere as being the sum of 250 harmonic terms of equal amplitude but with periods ranging uniformly from 12 minutes to 50 hours. Thus the interior of the model was forced by the periodic

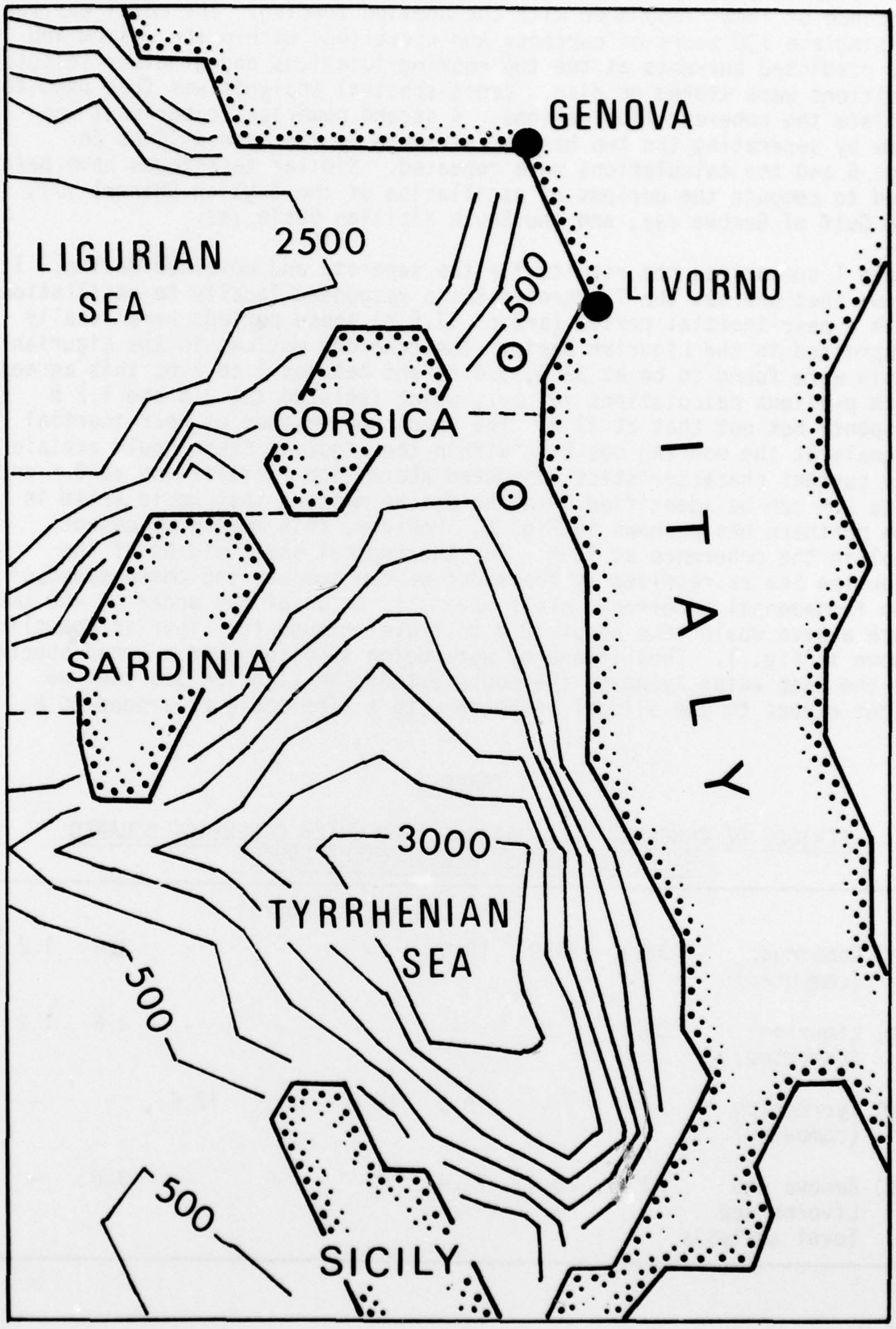


*FIG. 6 BOTTOM TOPOGRAPHY OF THE LIGURIAN AND TYRRHENIAN BASINS, AS USED IN THE NUMERICAL STUDY. Mooring locations are circled. The area shown is approximately 550 X 380 km² and the grid size is 20 km. The dashed lines represent the boundaries used to separate the two basins.*

elevations along the left-hand boundary, and we shall be looking for evidence of local resonance with the applied forcing. The model was run to simulate 100 hours of currents and elevations within the system and the predicted currents at the two mooring locations and at other selected positions were stored on disc. Cross-spectral analysis was then used to isolate the coherent fluctuations. A second numerical experiment was made by separating the two basins, as shown by the dashed lines in Fig. 6 and the calculations were repeated. Similar techniques have been used to compute the periods of oscillation of the English Channel *[7]*, the Gulf of Genova *[8]*, and the South Sicilian Basin *[9]*.

Table 1 summarizes the results for the separate and combined basins. It shows that whereas the Tyrrhenian Basin responded locally to oscillations with a near-inertial period (around 17.5 h) these periods were locally suppressed in the Ligurian Basin. The coherent motions in the Ligurian Basin were found to be at 33 h, 3.6 h, and between 1 to 2 h; this agrees with previous calculations *[8, 10]*, which isolated the 3.6 and 1.2 h response but not that at 33 h. The local suppression of near-inertial signals at the mooring position within the Ligurian Basin could explain the current characteristics discussed above. The oscillations at 3.6 and 1 to 2 h can be identified with the seiche motions that would arise in the northern basin shown in Fig. 6. However, this mechanism cannot explain the coherence at 33 h. For the typical shelf widths of the Ligurian Sea as resolved by the model we can compute the phase speed of the fundamental barotropic shelf wave *[11]* to be of the order of 400 km/day; such a wave would take about 30 h to travel around the Ligurian coastline shown in Fig. 1. Thus if energy were being supplied over a broad spectrum by the deep water lying to the southwest of the Ligurian Sea then we might expect to see a local response with a time scale of around 30 h.

TABLE 1

PERIODS OF COHERENT FLUCTUATIONS (FOR WHICH COHERENCE SQUARED EXCEEDED THE 95% SIGNIFICANCE LEVEL)

| | (Period in hours) | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| (a) Combined (computed) | 33.1 | 25.0 | 19.9 | - | - | - | 3.6 | 1.2 |
| (b) Ligurian (computed) | 33.1 | - | - | - | - | - | 3.6 | 1.2 |
| (c) Tyrrhenian (computed) | - | - | 19.9 | 16.6 | 14.2 | 12.4 | - | - |
| (d) Genova and Livorno sea level analysis | 33.4 | 25.4 | 21.4 | - | - | - | 3.6 | - |

An independent check of the calculations was made by analysing hourly, unfiltered, two-month long, sea-level records from Genova and Livorno (Fig. 1). The records were coherent at all periods longer than 4 days (due mainly to barometric effects) and also at the periods given in Table 1. Good agreement was found between the periods computed by the model and those isolated from the elevation data. In particular, evidence was obtained for periodicities within the Ligurian Basin at 33 and 3.6 h.

## DISCUSSION

The observational data suggest that the coastal waters of northwest Italy may not respond like a straight, open coastline (e.g. like the west coast of the United States) but may instead have characteristics more similar to a large enclosed lake. Thus the dominant response to forcing may involve the dynamics of the entire Western Mediterranean. Consequently work is now in progress to resolve the normal modes of the western basin and to look for a possible 5-day periodicity. Alternatively, the weather systems themselves may be more spatially coherent at the 5-day time scale and may thus be more efficient at driving the coastal response: this possibility is also being investigated further.

The data analysis has made use of a 'large-scale wind', which was obtained by computing the vector mean of several coastal wind records. In view of the poor coherence found between this wind and the coastal currents it suggests that this may not be a meaningful approach. It may be necessary to specify the wind everywhere (as is done in modelling the storm surge effects in the North Sea, e.g. [5]) in order to obtain a satisfactory prediction of the coastal response.

Returning to the problem of acoustic variability in the coastal waters, we can make some estimate of the effects of the coastal currents. From the observations, the alongshore current had an amplitude of around 7.0 cm/s at the 20-day time scale: this is equivalent to a maximum displacement of the water of about 6.1 km in one day. Since the maximum observed gradient in sound speed was about 0.1 m/s per km the current could produce a change of about 0.60 m/s from one day to the next at a fixed location. In comparison, seasonal heating caused an increase in sound speed of about 0.26 m/s per day. Thus, even in this region of extremely low horizontal gradients, the currents may have contributed significantly to the day-to-day variability in sound speed. Therefore in other areas, especially near frontal locations, accurate prediction of acoustic characteristics will not be obtained until we have a better understanding of the dynamics of the coastal zone.

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